Spectrum Broadening due to Nonselective Linear Absorption

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The position and linewidth of emission spectrum reflect the physical information inside an object observed. So keeping them from distortion is very important in the measurement of spectrum. However, the emission spectra are not always kept their forms. We let the near-infrared emission of a sodium lamp pass through a nonselective linear absorbing filter and then observe the emission spectrum. It is found that the spectral lines will be broadened when the power of the emission just after the filter becomes low enough, and the lower the transmittance of the filter is, the more obvious the effect is. This is another broadening effect different from the known ones and is likely to be another independent evidence for discrete wavelet structure of classical plane light waves.

Keywords: spectrum broadening, discrete wavelet structure of plane waves, nonselective linear absorption

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1. Introduction

A spectrum is like a fingerprint that can be used to identify the atoms, elements or molecules[1] in laboratory, and can be also used to identify the atoms, elements or molecules that are present in a star, galaxy or cloud of gas.[2] So spectroscopy is widely used in physics,[3] chemical industry,[4] micro-nano processing technology,[5] biopharma ceuticals[6] and Astronomy[7]. The particle will radiate the light wave in the process of transition from excited state to lower energy state, producing the emission spectrum and forming a spectral line with a certain width due to its finite lifetime in the excited state. The spectral line is usually described by the Lorentzian line profile.[3] The Doppler effect caused by molecular thermal motion can broaden the spectral line so that it becomes a Gaussian line profile,[3,8] and the spectral line may also be affected by particle collisions, lattice vibrations, defects and other factors, resulting in complex Voigt line profile broadening.[9] In addition, the Hubble redshift of spectral lines originating from the Doppler effect has been found in cosmological studies.[10,11] In 1986, Wolf proposed that if the spatial coherence of the light source satisfies a certain scaling law, the normalized spectrum of light will remain unchanged when it propagates through free space,[12] but if the scaling law is broken, for example, the spatial coherence of the light source is frequency-dependent,[13] or the fluctuation of the scattering kernel is random in space and time, the normalized spectrum also appears to be red-shifted when viewed from a long distance.[14,15] The position and

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linewidth of emission spectrum reflect the physical information inside an object observed. So keeping them from distortion is very important in the measurement of spectrum. However, the emission spectra are not always kept their forms. Recently, Zhang et al. found in the Michelson interference experiment of He-Ne laser beams that the coherence length of the light will decrease with the decrease of the power when the output laser beam passes through a nonselective linear absorbing medium and the power becomes low enough.[16] This means that, during the measurement, the nonselective linear absorption of the optical path system may change the linewidth of the spectrum. This is because, $\Delta\nu \cdot L / c \sim 1$, the shortening of the coherence length L may lead to the broadening of $\Delta\nu$, where $\Delta\nu$ is spectral linewidth, and c is light speed in vacuum. If the experimental conditions are appropriate, this effect would be observed. We found that the sodium lamp has several near-infrared spectral lines with linewidths in the range of 0.15-0.22 nm, which are suitable for this study because their broadening can be observed with a spectrometer with moderate resolution. As is expected, in the experiment of sodium lamp emission spectrum, we did observe a significant spectral broadening due to nonselective linear absorption.

2. Experiment Results and Discussion

Recently, based on the discrete wavelet structure theory of classic plane light waves proposed by Zhang and She,[17] Zhang et al. regarded the light from a He-Ne laser as a set of independent basic wave trains with discrete wavelet structure, and derived a formula for the variation of the coherence length of a light wave passing through a nonselective linear absorbing medium.[16]

$$L = \frac{(1 + CP_0)T}{1 + CP_0 T} L_0 , \tag{1}$$

where, T is the light intensity transmittance independent of reflection and scattering, and only related to nonselective linear absorption; C is a parameter; P_0 is the incident power of the light, L_0 is the coherence length of the incident light, and L is the coherence length of the outgoing light. The prediction of the formula was found to be consistent with the experiment.[16] According to Eq.(1) and the relationship $\Delta\nu \cdot L / c \sim 1$ with $\Delta\nu = c\Delta\lambda / \lambda^2$, We can get

$$\Delta\lambda \approx \frac{1 + C P_0 T}{(1 + C P_0)T} \Delta\lambda_0 , \tag{2}$$

where $\Delta\lambda_0$ is the spectral linewidth of the incident light and $\Delta\lambda$ is that of the outgoing light at wavelength λ. From Eq.(2), we noticed that the spectral linewidth

will change due to nonselective linear absorption, and the change is determined by the function $F(T)=(1+CP_0T)/[(1+CP_0)T]$. Pay attention to P_0, which is the incident power related to an observed spectral line. In order to see the dependence of spectral linewidth $\Delta\lambda$ on the incident power P_0 and transmittance T, we use the parameter $C=1.76\times10^9W^{-1}$ from Ref.[16]. For four incident values of light power $P_0=2\times10^{-6}$, 4×10^{-6}, 1.2×10^{-5} and $2\times10^{-5}W$, we calculate respectively the function $F(T)$ and the curves are shown in Fig.1. As can be seen from Fig.1, when $P_0\geq1.2\times10^{-5}W$ and $T\geq2\times10^{-4}$, the spectral line broadening effect is rather small, but when $P_0\leq2\times10^{-6}W$ and $T\leq2\times10^{-4}$, the spectral linewidth will broaden significantly. That is to say, the spectral line broadening effect is easy to be observed if the spectral line is with small initial light power. And the smaller T is, the more significant the spectral line broadening is. However, if the initial light power is too low and T is too small, the power of the light reaching the detector is too low, the noise will mask the effect of spectral broadening and make it impossible to observe. Therefore, in the experiment, the spectral line with appropriate linewidth and initial light power should be selected according to the resolution and signal-to-noise ratio of the spectrometer. We have found that there are several spectral lines in the near-infrared region of a sodium lamp, which are suitable for the observation of this effect.

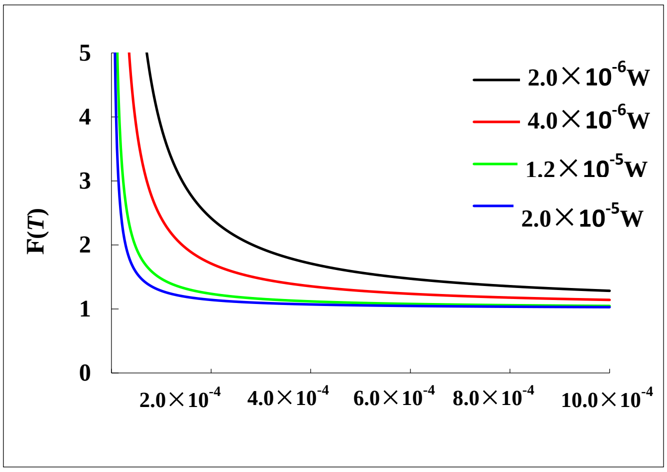

Fig.1: Spectral linewidth versus transmittance of non-selective linear absorption filter. The incident power of light onto the filter P_0 is 2×10^{-6}, 4×10^{-6}, 1.2×10^{-5}, and 2×10^{-5} W, respectively, where the parameter $C=1.76\times10^9\ W^{-1}$ is from Ref.[16].

We take a sodium lamp of laboratory as the light source and select an optical fiber spectrometer（AmSpec-ULS3648-USB2）with a nominal resolution of 0.21-0.25 nm for the experiment. The spectrometer has a high signal-to-noise ratio for weak near-infrared light and is suitable for observing the broadening effect of the spectrum. In the experiment, a convex lens with diameter of 35 mm and focal-length of 40mm was placed at a distance of 23 cm from the exit of the sodium lamp to focus the sodium lamp light onto the free end of lead-in fiber of the spectrometer. The focused beam does not have to be fully coupled into the fiber, as long as it hits the fiber entrance. A nonselective linear absorption filter was placed close to the fiber entrance. It should be noted that the spectral linewidth calculated by Eq.(2) corresponds to the light passing through the filter and does not depend on the optical power entering the optical fiber. We assume, of course, that the absorption of the fiber is negligible and that the light entering the spectrometer is sufficient to produce an observable signal.

The experiment involves two steps. The first one, we remove the filter and optical fiber, measure the total power of 720-830 nm near-infrared light at the focus, and then calculated the incident power of each spectral line onto the filter in according to the intensity distribution of spectral lines (remove the convex lens and then measure it with present optical fiber spectrometer). The results are shown in Table 1.

Table 1. Wavelengths and powers of near-infrared spectral lines of sodium lamp in the wavelength range of 720-830 nm.

	1	2	3	4	5	6	7	8	9
Wavelength (nm)	738.22	750.30 751.33	763.33	772.23	794.66	801.12 801.27	810.15 811.29	818.13 819.27	826.23
power (μW)	3.83	2.40 2.91	12.25	3.86	2.92	1.29 3.62	3.62 12.04	18.51 30.80	2.18

According to the above discussion, the spectral line with large power is not suitable for observation in this experiment, and the spectral line with double-line structure is not suitable for observation either, because it makes the situation more complex for analyzing the broadening effect. In addition, due to the limitation of resolution, the spectrometer cannot show the broadening effect of the spectral line with too narrow linewidth. In order to understand the linewidths of several spectral lines we concerned, we used the WPG-50Z grating spectrometer to measure them. The spectrometer has a resolution of 0.05 nm and can measure the linewidths of unattenuated emission spectrum of sodium lamp (but for weak light, the spectrometer has a low signal-to-noise ratio, so it is not suitable for observing the broadening effect). The linewidths measured are shown in Table 2.

Table 2. Linewidths of 5 near-infrared spectral lines of sodium lamp

Wavelength (nm)	738.22	763.33	772.23	794.66	826.23
linewidth (nm)	0.05	0.18	0.17	0.15	0.22

It can be seen from table 2 that the linewidth of 738.22 nm line is too narrow, which is not suitable for observing the broadening effect in present spectrometer. It is found that there is an unstable line near the 772.23 nm line (at 769.75 nm), which would cause disturbance and 772.23 nm line is not suitable for observation either. Therefore, in the second step, we put again the filter and the lead-in fiber of spectrometer, and select three spectral lines 763.33 nm，794.66 nm and 826.23 nm for observation. In the experiment, the integration time of each measurement is taken as 12 s and the average was taken as 1. In order to minimize the influence of environment and measurement system noises, the dark background signal is recorded, saved, and deducted for each measurement, and for a selected T value of filter, the measurement is repeated 15 times, and the average is taken as the result. Fig.2-4 show three groups of experimental results.

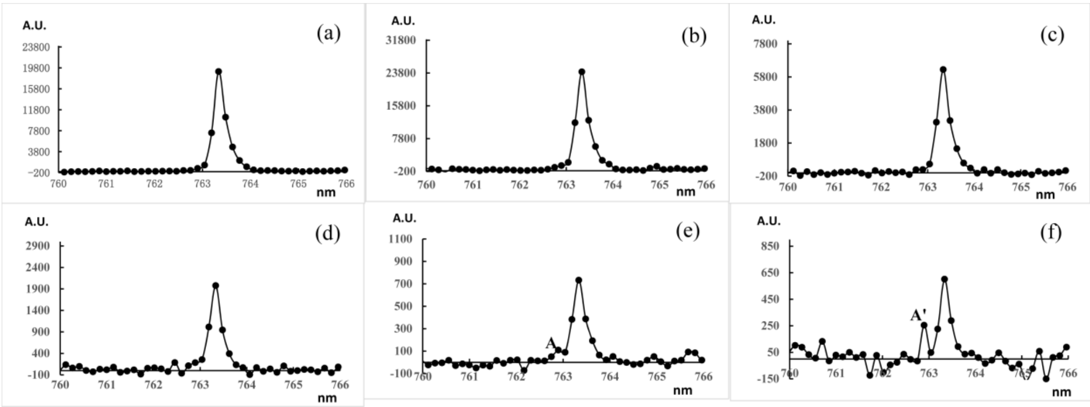

Fig.2：Spectrum broadening due to nonselective linear absorption at 763.33 nm, where, a is the spectral line without passing through the filter; b-f are the spectral line after passing through the filter, corresponding respectively to transmittances of the filter: 8.00×10^{-4}, 1.91×10^{-4}, 0.46×10^{-4}, 0.22×10^{-4} and 0.14×10^{-4}.

The spectral line broadening at 763.33 nm is shown in Fig. 2. Where Fig.2a is the experimental result with filter and lens removed (the same for subfigure a in Fig.3-4 below). The transmittances of the filter corresponding to Fig.2b-f are 8.00×10^{-4}, 1.91×10^{-4}, 0.46×10^{-4}, 0.22×10^{-4} and 0.14×10^{-4}, respectively. According to Eq.(2), we calculate the linewidths of $\Delta\lambda$ after the filter. The results are 0.20 nm, 0.24 nm, 0.38 nm, 0.59 nm and 0.82 nm, respectively. Although the first two linewidths values are slightly larger than $\Delta\lambda_0$ (= 0.18 nm), the broadening effect of the spectral line cannot be seen in Fig.2b-c due to the limitation of the resolution of the spectrometer. The last three calculated linewidths are reflected in Fig. 2d-f, but in Fig. 2d-f, the spectral line does not become fat in a whole, yet the side frequencies gradually appear in the short-wave direction (see the two small peaks A and A' in Fig. 2e-f).

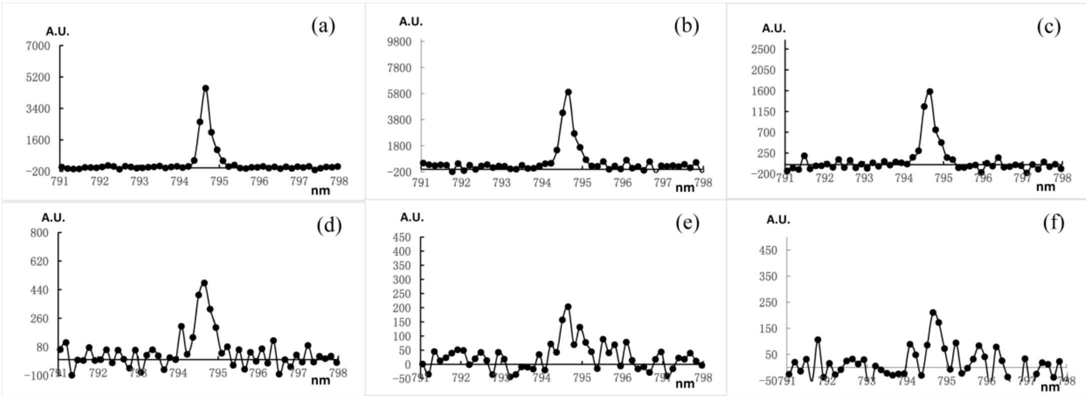

Fig.3：Spectrum broadening due to nonselective linear absorption at 794.66 nm, where, a is the spectral line without passing through the filter; b-f are the spectral line after passing through the filter, corresponding respectively to transmittances of the filter: 8.10×10^{-4}, 1.98×10^{-4}, 0.49×10^{-4}, 0.21×10^{-4} and 0.13×10^{-4}.

The spectral line broadening at 794.66 nm is shown in Fig.3. The transmittances of the filter corresponding to Fig.3b-f are 8.10×10^{-4}, 1.98×10^{-4}, 0.49×10^{-4}, 0.21×10^{-4} and 0.13×10^{-4}, respectively. According to Eq.(2), we calculate the linewidths of $\Delta\lambda$ after the filter. The results are 0.20 nm, 0.32 nm, 0.79 nm, 1.64 nm and 2.55 nm, respectively. The difference between the calculated linewidth of 0.20 nm and $\Delta\lambda_0$（$=0.15nm$） is very small, and the broadening effect cannot be embodied due to the limitation of the resolution of the spectrometer (see Fig. 3b). The calculated linewidth of 0.32 nm is larger than $\Delta\lambda_0$, but the broadening effect can only slightly be seen in Fig.3c also due to the limited resolution of the spectrometer. The calculated linewidth of 0.79 nm is obviously larger than $\Delta\lambda_0$, which is basically consistent with Fig.3d. Although there is noise in Fig.3e, the trend of line broadening can be seen, which is also basically consistent with the result calculated. Despite the noise in Fig.3f is large and quantitative comparison is difficult, the spectral line broadening effect can still be seen faintly.

Fig. 4 shows the spectral line broadening at 826.22 nm. The transmittances of the filter corresponding to Fig.3b-f are 8.30×10^{-4}, 1.99×10^{-4}, 0.47×10^{-4}, 0.20×10^{-4} and 0.13×10^{-4}, respectively. According to Eq.(2), we also calculate the linewidth $\Delta\lambda$ of after the filter. The results are 0.29 nm, 0.51 nm, 1.44 nm, 3.10 nm and 4.66 nm, respectively. The first three calculated values of linewidth are basically consistent with those in Fig.4b-d, but the broadening of the spectral line does not become fat in a

whole, yet the spectral line splits and produces side frequencies. This is consistent with the case of Fig. 2. Note that the positions of two peaks A' and B' in Fig. 4d correspond to two peaks A and B in Fig. 4c. In addition, there are two small peaks C' and D' in Fig.4d, which correspond to the positions of two small peaks C and D in Fig.4c, as if not being noise. The noise in Fig.4e is large and difficult to make comparison quantitatively, but its broadening effect can still be seen faintly, in which three peaks A'', B'' and E'' correspond to those of A', B' and E' in Fig.4d, respectively. Spectral line in Fig.4f is basically submerged in noise after deformation, and cannot be compared with the calculated result.

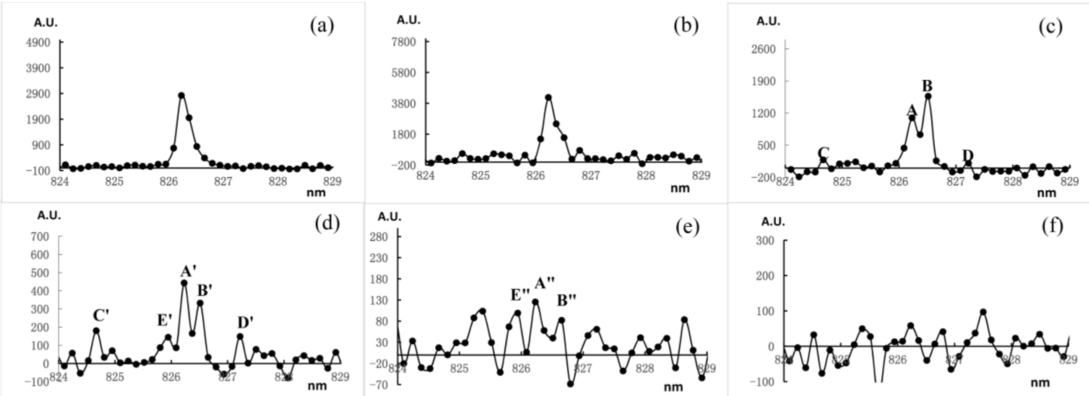

Fig.4 Spectrum broadening due to nonselective linear absorption at 826.22 nm, where, a is the spectral line without passing through the filter; b-f are the spectral line after passing through the filter, corresponding respectively to transmittances of the filter: 8.30×10^{-4}, 1.99×10^{-4}, 0.47×10^{-4}, 0.20×10^{-4} and 0.13×10^{-4} .

Comparing these three groups of experimental results, it is easy to see that they are consistent with the prediction of Fig.1, that is, the lower the incident light power onto the filter is, the easier it is for observing the broadening effect of spectral line. It should be noted here that the spectral broadening effect described above cannot be caused by the reduction of the light power due to reflection, scattering, polarization isolation, etc. Scattering may be one of the most disturbing factors for observing this effect, because the light with short wavelength is with strong scattering and this scattering will lead to a decrease of the transmittance of the filter, which can be mistaken as the effect of absorption. Therefore, to observe present effect it is best to perform the experiment in the long-wave band.

3. Conclusions

In summary, the attenuation of the near-infrared emission of a sodium lamp is studied by using a nonselective linear absorption filter, and it is found that the spectral line of the emission spectrum will be broadened when the power through the filter becomes low enough due to linear absorption, and the lower the transmittance of the filter is, the more obvious the effect is. This is another one different from the known

spectrum broadening effects. It should be paid attention to this effect in spectral experiments, especially in high-sensitive spectral experiments such as in streak camera spectral experiment, where a non-selective linear absorption filter is often used to attenuate the light signal originally with weak intensity. This may cause the spectrum broadening of the light signal and make the recorded physical information distorted. In addition, this effect may also have its significance for reference in cosmological research. Because the light from distant stars is weak when it reaches Earth, and because the light has traveled a long space path, most likely through a thick absorbing medium of galaxies, the spectral broadening effect described here may occur, which may be superimposed on the Habble redshift effect[18] and the redshift effect predicted by wolf.[14] Besides, this effect is likely to be another independent evidence for discrete wavelet structure of classical plane light waves.[17]

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